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Intersecting Inequalities: A Household-Level WEF Nexus Assessment in Thabo Mofutsanyane District, South Africa

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Abstract: Sustainable resource management remains markedly uneven in South Africa's climate-sensitive, semi-arid regions, where ecological stress intersects with persistent socioeconomic inequality. Although the Water–Energy–Food (WEF) nexus is increasingly promoted as an integrated framework, limited empirical evidence exists on how household-level resource access and climate perceptions interact across rural and urban settings. This study addresses that gap through an index-based WEF nexus assessment in the Thabo Mofutsanyane District of the Eastern Free State. A cross-sectional survey of 400 households was conducted across four ecologically diverse towns: Phuthadjithaba, Ladybrand, Marquard, and Vrede, using multi-stage sampling. Three composite indices were developed and standardised (0–1 scale): the Water Access Index (WAI), Energy Access Index (EAI), and Natural Resource Use Index (NRUI). Data were analysed using descriptive statistics, chi-square tests ($\alpha = 0.05$), and multiple linear regression models. The results reveal significant urban–rural disparities in education, household size, housing type, and formal water access ($p < 0.05$). Water source and drought perception significantly predict WAI; education and climate perception influence EAI; while settlement type, gender of household head, and rainfall awareness shape NRUI ($p < 0.05$). These findings highlight clear socio-spatial inequalities and underscore the need for integrated, context-specific resource governance to enhance resilience in semi-arid regions.

Keywords: Water access index, natural resources, water energy, food nexus, ecological intensity, energy access index.

1. Introduction

Sustainable resource management in South Africa unfolds within a context of climate variability, ecological stress, and persistent socioeconomic inequality. In rural and peri-urban areas, households rely on interconnected water, energy, and food systems to sustain their livelihoods; however, these systems are increasingly destabilised by recurrent droughts, erratic rainfall, and land-use changes (Esan et al., 2024; Gandidzanwa & Togo, 2024). Most climate impacts in the region are water-related, suggesting that interventions in water access can yield cascading benefits across the energy and food sectors.

The Water–Energy–Food (WEF) Nexus provides a conceptual framework for analysing the interdependencies between these resources. It recognises that water availability influences food production and energy generation, while access to energy affects water abstraction, treatment, and food preparation (de Souza et al., 2022). However, inequality significantly impacts these relationships. Variations in access to income, infrastructure, land, and institutional support determine how households experience and respond to resource constraints. Inequality functions both as a driver and an outcome of WEF interactions: Limited water access restricts food security and livelihood options, which in turn diminishes the ability to secure energy and invest in adaptive

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strategies. Consequently, the WEF Nexus and inequality are mutually reinforcing processes that operate through social, economic, and ecological pathways.

Empirically, the majority of WEF Nexus studies conducted in South Africa and elsewhere have concentrated on macro- or regional-scale modelling, with limited attention paid to household-level dynamics and lived experiences (Mabhaudhi et al., 2019; Nhamo et al., 2019; Jaka et al., 2023). Existing approaches often prioritise technical optimisation and quantitative resource flows, frequently overlooking how factors such as gender, education, livelihood diversity, governance quality, and perceptions of climate shape household decision-making and resilience (Chirenje et al., 2021). These gaps are particularly pronounced in transitional landscapes such as the Eastern Free State, where formal infrastructure coexists with informal and nature-based resource practices. In the Thabo Mofutsanyane District Municipality, including Phuthadjithaba, water insecurity linked to declining dam levels, infrastructure deficits, and governance challenges has exacerbated household vulnerability and social tensions (Mukwada & Mutana, 2023; Sekhele & Otomo, 2023). Nevertheless, little empirical research has systematically examined how inequalities in access to water, energy, and natural resources intersect at the household scale within such contexts. To address this gap, this study applies the WEF Nexus framework at the household level in the Thabo Mofutsanyane District and explicitly investigates its interaction with inequality. We develop three composite indices: the Water Access Index (WAI), the Energy Access Index (EAI), and the Natural Resource Use Index (NRUI)—to capture resource availability, the diversity of access pathways, and associated socioeconomic and ecological pressures. Building on access theory (Ribot & Peluso, 2003; Ribot & Peluso, 2003) and scholarship on inequality (Stewart & Samman, 2013; IPCC, 2022), we conceptualise access as socially mediated and shaped by power, assets, and institutional arrangements.

The study is guided by the following research questions: (1) How is access to water, energy, and natural resources distributed across households in Thabo Mofutsanyane District? (2) How do inequalities in one WEF component influence outcomes in the others? (3) Which socioeconomic factors most strongly explain variation in composite WEF access indices? Accordingly, the objectives are to: (i) construct and apply household-level WEF access indices; (ii) analyse the interrelationships among water, energy, and natural resource access; and (iii) assess how socioeconomic inequalities shape these interactions. A conceptual framework (Figure 1) illustrates the theoretical pathways linking WEF components and inequality, positioning households at the centre of mutually reinforcing resource and social dynamics.

1.1 Theoretical and conceptual framework

To establish a coherent conceptual foundation for this study, we present a framework that connects WEF Nexus theory, socio-ecological inequality, and the role of composite indices in development analyses. The WEF Nexus theory posits that water, energy, and food systems are profoundly interdependent (Leck et al., 2015; Srigiri & Dombrowsky, 2022) and that holistic management of these interconnections is essential for addressing resource security, resilience, and sustainable development in the context of changing climate conditions (Leck et al., 2015; Pahl-Wostl, 2019). Recent scholarship has underscored that effective governance of the nexus must transcend biophysical interdependence and explicitly incorporate social dimensions, as access, power, and governance structures significantly influence resource outcomes and community resilience (Ratner et al., 2013). Furthermore, frameworks addressing socio-ecological inequality indicate that unequal access to resources for mitigation and adaptation exacerbates vulnerabilities and shapes perceptions of climate risks and policies across different populations (Zahnow et al., 2025). Finally, composite indices such as the WEF nexus composite index provide quantitative tools to synthesise multidimensional data on resource availability, accessibility, and governance, constructing a coherent metric that bridges sectoral complexities and facilitates comparative development analysis (Christopoulos, Horvath & Kull, 2012; Simpson & Jewitt, 2019). By integrating these elements, our framework situates climate perception as being influenced by both structural inequalities and the interconnected dynamics of WEF systems, thereby enhancing theoretical clarity and global relevance in accordance with recent high-impact literature.

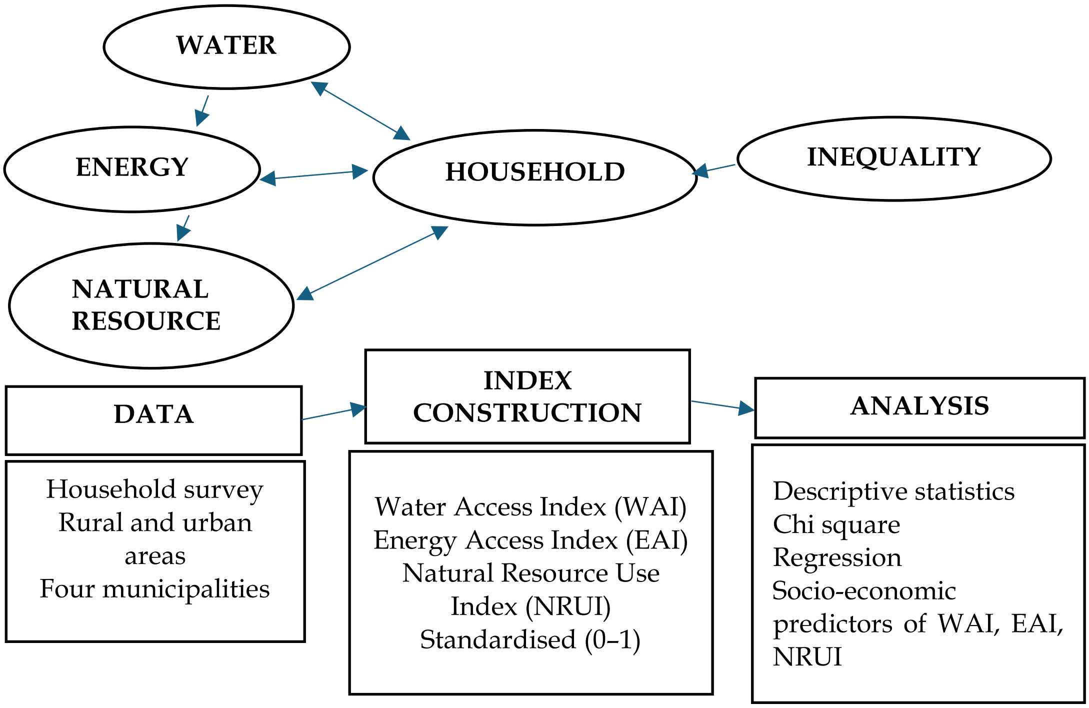

***Figure 1**: Integrated framework of WEF–inequality dynamics and methodological flow*

2. Materials and Methods

This study employed a quantitative research methodology, utilising a cross-sectional household survey design. A quantitative approach was deemed suitable as the research aimed to measure household-level access to water, energy, and natural resources, construct composite indices, and statistically evaluate the impact of socioeconomic factors on these indices. The cross-sectional design facilitated the collection of standardised data from multiple households at a singular point in time (February–March 2021), thereby enabling comparative and inferential analyses across various settlement types and ecological zones. Furthermore, the study was structured as an index-based sustainability assessment, grounded in the Water-Energy-Food (WEF) nexus framework. This framework acknowledges the interdependencies among water access, energy systems, and natural resource utilisation, particularly in climate-sensitive, semi-arid environments. This study was conducted in four towns - Phuthadjithaba (Maluti-a-Phofung Municipality), Ladybrand (Mantsopa Municipality), Marquard (Setsoto Municipality), and Vrede (Phumelela Municipality), all of which are located within the Thabo Mofutsanyane District (Figure 2).

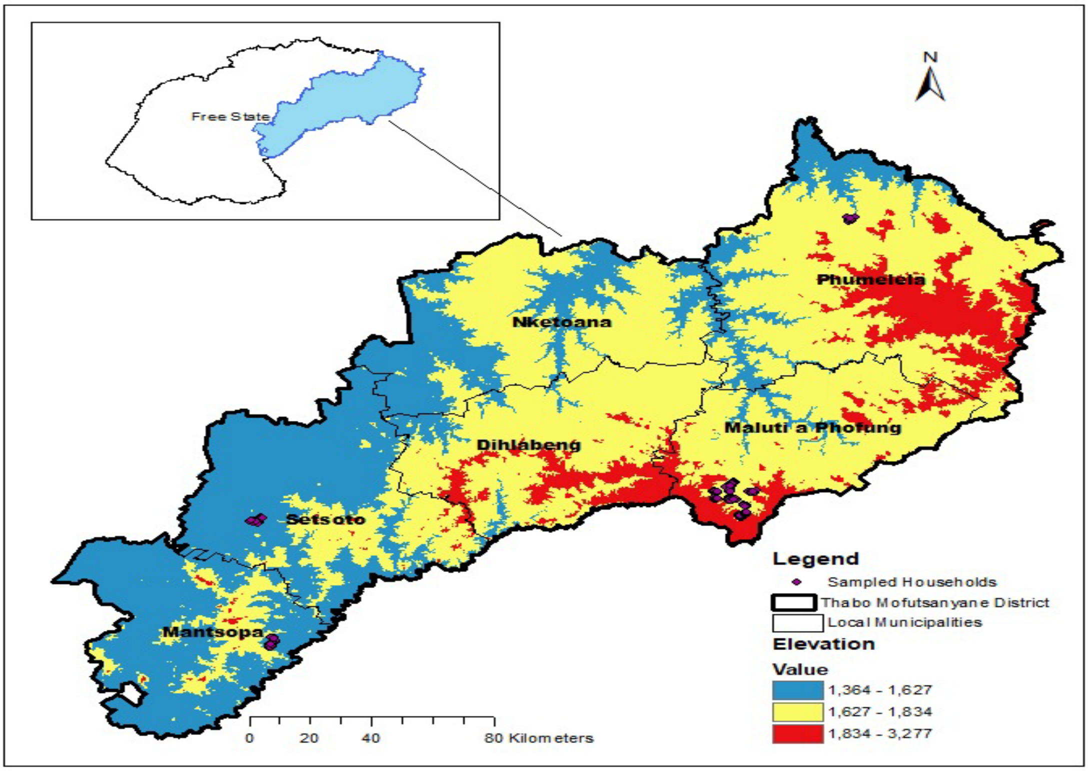

Figure 2: *Study area*

These municipalities were purposively selected for three main reasons: ecological variability, as the district is semi-arid and characterised by significant elevation differences that influence water availability and household energy needs; rural–urban diversity, since the selected towns reflect a mix of peri-urban and rural settlement patterns; and resource dependency patterns, given that winter temperatures often fall below -10 °C, leading to heavy reliance on firewood and other biomass resources for heating and cooking. The combination of ecological variation and diverse settlement characteristics made the district particularly suitable for examining disparities in household resource access within a Water–Energy–Food (WEF) nexus framework.

The study population consisted of 179,508 households in the Thabo Mofutsanyane District (Community Survey, 2016). To determine the sample size, the Yamane (1967) formula was applied at a 95% confidence level and 8% precision, which resulted in a minimum sample size of approximately 400 households. This total was then proportionally distributed across the four municipalities according to their household counts. For example, Verde, with population size of 50,054, was sampled as 33 households (50,054/574,393 × 400 = 33). Phuthadjithaba, with population size of 353,453, was represented by 247 households (353,453/574,393 × 400 = 247). Marquard, with 37,246 population size, was sampled as 83 households (37,246/574,393 × 400 = 83). Ladybrand, with 16,951 population size, was sampled as 38 households (16,951/574,393 × 400 = 38). Thus, the 400 households constitute a statistically adequate and representative sample for the district under standard confidence assumptions. A multi-stage sampling strategy was employed to ensure that the study captured a comprehensive and meaningful representation of the district. Initially, four municipalities were purposively selected to reflect the area's ecological and settlement diversity. Subsequently, within each municipality, communities were categorised into high- and low-elevation zones to account for variations in climate and infrastructure that could influence access to water and energy. Households were then randomly selected from both rural and urban sections of each municipality. To uphold fairness and representativeness, the number of households sampled in each town was proportionate to its population size.

2.1 Data collection and analysis

Data were collected between February and March 2021 using a structured household questionnaire designed to gather comprehensive and reliable information. The survey captured key socioeconomic characteristics, including income, education, and household size, as well as details on access to water sources, patterns of energy use, natural resource utilisation, and perceptions of climate variability. Most questions were closed-ended to facilitate efficient quantitative analysis, while a limited number of open-ended responses were systematically coded into numerical categories prior to analysis. Ethical clearance was obtained from the University of the Free State's General/Human Research Ethics Committee (GHREC). (Ethical Clearance number: UFS-HSD2020/1277/0709). Informed consent was secured from all participants, and stringent measures were implemented to ensure confidentiality and anonymity throughout the study.

2.1.1 Construction of composite indices

Three composite indices were developed for the study: the Water Access Index (WAI), the Energy Access Index (EAI), and the Natural Resource Use Index (NRUI). Each index was standardised on a scale ranging from 0 to 1 to ensure comparability across variables and facilitate interpretation. The construction of these indices followed established approaches in composite indicator development, enabling the aggregation of multiple dimensions into coherent measures of access and resource use. Weights of 0.6 and 0.4 were assigned to selected components based on guidance from existing literature on composite index construction, the contextual importance of reliability in semi-arid environments, and sustainability considerations that prioritise ecological impacts. While the use of expert-informed weighting inevitably introduces a degree of subjectivity, it remains consistent with widely accepted methodologies for sustainability indices. To enhance robustness, a sensitivity analysis was conducted, demonstrating that moderate adjustments in weighting did not significantly change the overall ranking patterns of the indices.

2.1.2 Statistical analysis

Data were analysed using IBM SPSS Version 31. The analysis began with descriptive statistics, including the calculation of means, standard deviations, frequencies, and cross-tabulations to summarise household characteristics and key study variables. Chi-square tests of independence were then performed to assess associations between categorical variables such as settlement type, education level, and climate perceptions. Statistical significance was evaluated at an alpha level of 0.05. Given that the WAI, EAI, and NRUI were continuous variables measured on a 0–1 scale, multiple linear regression models were employed to examine the effects of socioeconomic predictors on these indices. The general model specification was expressed as $(Y_i = \beta_0 + \beta_1X_1 + \beta_2X_2 + ... + \beta_nX_n + \varepsilon)$, where (Y_i) represented the respective index (*WAI, EAI, or NRUI*), (X) denoted the set of socioeconomic variables, and (ε) referred to the error term. Model diagnostics included assessment of multicollinearity using the Variance Inflation Factor (VIF), evaluation of residual normality, examination of adjusted R^2 values, and interpretation of F-statistics to determine overall model significance. In instances where categorical forms of the indices were analysed, ordinal logistic regression techniques were employed as appropriate. These census figures were excluded from the primary statistical analysis. All inferential analyses presented in this study are based exclusively on the primary survey data from 2021.

3. Results and Discussion

This section outlines the principal findings from a household-level survey conducted in selected municipalities in the Eastern Free State Region. The findings highlight regional and socioeconomic discrepancies in access to resources, livelihood strategies, and environmental perceptions. Particular attention is given to the Water Access Index (WAI), Energy Access Index (EAI), and Natural Resource Use Index (NRUI), which reveal patterns of resource dependence, ecological pressure, and the limits of household adaptive capacity. The spatial scope of the sample is confined to specific areas within the district, which may restrict the applicability of the findings to other regions or municipalities.

3.1 Socio-demographic profile of respondents

The household survey (n = 400) across selected municipalities in the Eastern Free State reveals statistically significant urban–rural disparities in education ($\chi^2 = 32.096$, $p < 0.001$), household size ($\chi^2 = 21.397$, $p < 0.001$), employment status ($\chi^2 = 33.138$, $p < 0.001$), water source ($\chi^2 = 61.203$, $p < 0.001$), and type of shelter ($\chi^2 = 23.664$, $p < 0.001$). No significant differences were observed for land ownership or household status. These spatial inequalities directly shaped resource access outcomes captured through the Water Access Index (WAI), Energy Access Index (EAI), and Natural Resource Use Index (NRUI).

3.1.1 Urban–rural differences

The comparison between urban and rural households revealed several statistically significant differences across socio-demographic and resource access variables (Table 1). Respondent age differed notably by settlement type ($\chi^2 = 15.986$, $p = 0.003$), with urban areas exhibiting a higher concentration of middle-aged individuals, while rural areas had a larger proportion of older respondents. Education level also differed significantly ($\chi^2 = 32.096$, $p < 0.05$), with urban households more likely to have higher educational qualifications, whereas rural households were concentrated in lower education categories. These findings mirror broader national patterns of educational inequality and rural underinvestment (Spaull, 2015). Household size followed a similar trend ($\chi^2 = 21.397$, $p < 0.05$), with urban households tending to be larger and more diverse in composition, while rural households were generally smaller. Water source also revealed pronounced disparities ($\chi^2 = 61.203$, $p = 0.000$): urban households relied predominantly on formal water systems, while rural households depended more on informal or natural sources, reflecting persistent infrastructure gaps across rural South Africa (Mabhaudhi et al., 2019).

Table 1: *Chi-Square Test Results Comparing Urban and Rural Households Across Key Variables*

Variable	χ^2 Value	p-value
Household Head	0.871	0.351
Age of Respondent	15.986	0.003
Education Level	32.096	0.000
Household Size	21.397	0.000
Source of Water	61.203	0.000
Land Ownership	0.105	0.746
Livelihood Activities	25.354	0.000
Employment Status	33.138	0.000
Duration of Residence	29.755	0.000
Type of Shelter	23.664	0.000
Forest Resource Use	11.845	0.008
Drought Perception	0.001	0.974
Rain Season Precipitation Change	2.673	0.263
Water Availability Change	4.897	0.027

Bolded significance indicates $p < 0.05$.

Livelihood activities varied significantly across different settlement types ($\chi^2 = 25.354$, $p = 0.000$). Urban households tended to engage in either single livelihood activities or highly diversified strategies involving four distinct activities, indicating a divide between specialisation and diversification. In contrast, rural households demonstrated a more balanced distribution across two- and three-activity categories, reflecting moderate income diversification. Employment status also showed significant variation by settlement type ($\chi^2 = 33.138$, $p = 0.000$), underscoring distinct urban-rural economic dynamics. Additionally, the duration of residence indicated that rural households were more likely to have long-term tenure exceeding 21 years, while urban households exhibited a more varied distribution. These patterns reflect South Africa's dual economic structure, where rural communities largely depend on informal and subsistence-based livelihoods (Neves & Toit, 2013).

Housing types further highlighted spatial inequalities. Urban households predominantly lived in formal brick structures, whereas rural households exhibited greater variation, including informal and mixed housing types ($\chi^2 = 23.664$, $p = 0.000$). Similarly, engagement with forest resources differed by settlement, with rural households being more likely to harvest or both harvest and purchase forest products, while urban households relied more on market purchases or had minimal interaction ($\chi^2 = 11.845$, $p = 0.008$). These findings illustrate the interconnected nature of settlement, infrastructure, and resource dependence, reinforcing the need for tailored, place-based approaches within the WEF nexus framework (Jaka et al., 2023; Turok & Borel-Saladin, 2016).

Perceptions of climate variability showed both convergence and divergence across settlements. Rural households reported slightly greater changes in water availability ($\chi^2 = 4.897$, $p = 0.027$), although perceptions of drought ($\chi^2 = 0.001$, $p = 0.974$) and rainy-season precipitation ($\chi^2 = 2.673$, $p = 0.263$) were similar in urban and rural contexts. Household head status ($\chi^2 = 0.871$, $p = 0.351$) and land ownership ($\chi^2 = 0.105$, $p = 0.746$) displayed no significant differences, indicating relative parity in these attributes. Overall, the results highlight persistent spatial inequalities between urban and rural communities, particularly in livelihoods, infrastructure, and water access, which necessitate context-sensitive interventions to strengthen WEF nexus outcomes and support equitable resource management (Mpandeli et al., 2018).

3.2 Water Access Index (WAI)

WAI scores differed significantly across towns ($\chi^2 = 46.725$, $p < 0.05$). Phuthadjithaba exhibited the greatest dispersion across categories, including the highest concentration in Category 4 (high access). Ladybrand and Vrede were concentrated in Categories 2 and 3, indicating moderate but less secure access. Regression analysis identified the number of water sources as the strongest predictor of WAI (B = 0.578, Exp(B) = 1.783, p = 0.000). This indicates that each additional water source increases the odds of being in a higher WAI category by approximately 78%, demonstrating that source diversification substantially improves functional water security. Drought perception (B = 0.240, Exp(B) = 1.271, p = 0.001) increases the likelihood of higher WAI scores by 27%, suggesting adaptive behaviour among climate-aware households. Conversely, the number of livelihood activities (B = –0.047, Exp(B) = 0.954, p = 0.047) slightly reduces WAI (≈4.6% decrease per additional activity), indicating resource competition within diversified livelihood systems. Other socio-economic variables were not statistically significant, underscoring that infrastructural diversification outweighs demographic characteristics in determining water access.

Table 2: *Regression coefficients of WAI, EAI, and NRUI*

Predictor Variable	WAI			EAI			NRUI		
	(B)	Exp(B)	Sig	(B)	Exp(B)	Sig	(B)	Exp(B)	Sig
Education Level	0.000	1.000	0.981	0.057	1.059	**0.007**	-0.008	0.992	0.737
Household Size	-0.037	0.964	0.262	0.088	1.092	**0.009**	-0.008	0.992	0.842
Settlement type	0.042	1.043	0.504	-0.035	0.966	0.583	0.146	1.157	**0.040**

Duration of residence	0.011	1.011	0.677	0.040	1.041	0.129	0.064	1.066	**0.032**
NURI	0.054	1.055	0.231	0.264	1.302	**0.000**	-	-	-
EAI	0.071	1.074	0.158	-	-	-	0.336	1.400	**0.000**
WAI	-	-	-	0.073	1.076	0.158	0.070	1.073	0.231
Forest Resource Use	-0.043	0.958	0.248	0.003	1.003	0.942	-0.291	0.747	**0.000**
Household head gender	0.458	1.581	0.414	0.267	1.306	0.637	1.534	4.640	**0.016**
Perceived changes in water availability	0.018	1.018	0.772	-0.127	0.881	**0.045**	0.025	1.025	0.723
Perceived Rainfall change	0.004	1.004	0.920	-0.132	0.876	**0.003**	0.134	1.143	**0.007**
Number of water sources	0.578	1.783	**0.000**	0.185	1.203	**0.000**	-0.064	0.938	0.265
Drought Perception	0.240	1.271	**0.001**	0.047	1.048	0.535	0.001	1.001	0.994
Number of livelihood activities	-0.047	0.954	**0.047**	0.047	1.048	**0.049**	-0.048	0.953	0.074
Land ownership	-0.095	0.909	0.227	-0.047	0.954	0.559	0.084	1.088	0.348

Bolded indicates $p < 0.05$.

3.3 Energy Access Index (EAI)

Despite near-universal electrification (96.5%), households continue to rely on multiple fuel sources, with 40% using wood, 43.3% using gas, and 34.8% using paraffin, indicating a persistent trend of energy stacking. Consequently, grid connectivity does not guarantee exclusive or secure reliance on electricity; rather, households integrate various fuels to manage costs, reliability, and specific energy demands. The distribution of the Energy Access Index (EAI) varied significantly across towns ($\chi^2 = 36.041$, $p < 0.001$), with most households clustered in moderate access categories. This spatial differentiation highlights that nominal electrification obscures qualitative disparities shaped by local infrastructure, socioeconomic conditions, and environmental constraints. In this context, energy access is more accurately conceptualised as a continuum of reliability and adequacy, rather than a binary condition of connection.

Regression results elucidate the structural drivers of higher EAI. Education was positively associated with energy access (B = 0.057, Exp(B) = 1.059, p = 0.007), suggesting that enhanced human capital improves households' capacity to secure reliable energy through better income prospects and institutional navigation. Household size similarly increased the odds of a higher EAI (B = 0.088, Exp(B) = 1.092, p = 0.009), possibly reflecting pooled resources, although larger households also confront greater overall demand. Access to multiple water sources demonstrated a strong positive association (B = 0.185, Exp(B) = 1.203, p = 0.000), indicating that energy security is linked to broader infrastructural advantages. Additionally, the Natural Resource Use Index (NRUI) was positively related to EAI (B = 0.264, Exp(B) = 1.302, p = 0.000). While diversified natural resource use may suggest adaptive flexibility, it may also reflect a constrained reliance on biomass, highlighting the necessity to distinguish resilience from necessity-driven coping. Economic diversification exhibited a modest but significant effect (B = 0.047, $p = 0.049$), reinforcing evidence that multiple income streams enhance adaptive capacity, albeit unevenly.

In contrast, climate-related stressors were negatively associated with energy access. Perceived changes in precipitation (B = –0.132, Exp(B) = 0.876, $p = 0.003$) and water availability (B = –0.127, $p = 0.045$) diminished the likelihood of a higher EAI, suggesting that climatic variability compromises household energy security by disrupting livelihoods and purchasing power. Other factors such as settlement type, gender of household head, land ownership, and perceptions of drought were not statistically significant. Overall, the findings reveal that energy access outcomes arise from the interplay of infrastructural context, socioeconomic capacity, resource diversification, and climate stress. Although diversification in livelihoods and resource use is associated with improved access, its significance remains context-dependent, necessitating careful interpretation to avoid conflating adaptive resilience with structural vulnerability.

3.4 Natural resource use index (NRUI)

Forest products remain crucial for household livelihoods across the study area, although the pathways to access them differ. Among the 400 respondents, 43.3% reported purchasing forest resources, 17.8% harvested directly, and 5% employed both strategies, while 34% indicated no use at all. Market purchases thus represent the predominant mode of access, suggesting a growing commodification of forest goods and potential constraints on direct extraction, such as conservation controls or declining local availability. Firewood was the most commonly utilised resource (43.8%), followed by leaves (21%), roots (14.3%), seeds (13.8%), fodder (8.3%), and poles (2.5%). This underscores the multifunctional role of forest ecosystems in meeting energy needs and supplementary livelihood requirements. However, reliance on self-reported data and the absence of ecological indicators, such as forest cover change or harvesting intensity, limit conclusions regarding sustainability. Integrating household surveys with ecological assessments would enhance our understanding of environmental pressures and resource trends.

Spatial analysis revealed significant variation in NRUI scores across towns ($\chi^2 = 18.457$, $p = 0.030$), confirming that geographic context influences resource dependence. Phuthadjithaba exhibited the widest range of usage, from low to very high impact, while Marquard, Ladybrand, and Vrede were predominantly concentrated in low- and moderate-impact categories, with minimal representation in intensive-use groups. These patterns suggest that settlement structure, ecological endowment, and livelihood systems shape the scale and diversity of resource engagement. Environmental stressors, including drought, rainfall variability, and temperature fluctuations, likely exacerbate these dynamics by affecting biomass availability and ecosystem resilience. In contexts where biomass extraction may exceed regenerative capacity, localised indices such as the NRUI offer critical insights into household-level pressures and provide a pragmatic link between nexus-oriented policy frameworks and lived environmental realities.

Regression analysis further indicated that NRUI scores are influenced by social and institutional factors. Male-headed households reported significantly higher resource use (B = 1.534, $p = 0.016$), reflecting the gendered control over productive assets and decision-making authority observed in similar rural settings. Settlement type was positively associated with NRUI (B = 0.146, $p = 0.040$), indicating a stronger reliance among rural households, while longer residence (B = 0.064, $p = 0.032$) and perceived rainfall change (B = 0.134, $p = 0.007$) correlated with increased engagement with natural resources. Notably, forest resource use was negatively associated with NRUI (B = –0.291, $p = 0.000$), suggesting either a concentration in fewer resource categories or constrained diversification under conditions of scarcity or regulation. The Energy Access Index exhibited a strong positive effect (B = 0.336, $p < 0.05$), reinforcing the interdependence between energy systems and environmental resource use. Collectively, these findings indicate that reliance on natural resources is not solely ecological but is mediated by gender relations, settlement dynamics, climatic perceptions, and energy infrastructures, highlighting the need for integrated, context-sensitive policy responses.

5. Conclusions

This study utilised three composite indices: the WAI, EAI, and NRUI, to assess disparities in resource access among 400 households in the Eastern Free State within a WEF nexus framework. The findings reveal statistically significant urban-rural inequalities. Approximately 46.9% of rural households experienced moderate to low WAI, in stark contrast to a significantly higher proportion of urban households reporting a reliable formal supply. Similarly, 41.3% of rural respondents indicated unstable EAI, frequently associated with infrastructure deficits and affordability issues. Households that perceived increased variability in rainfall and recurrent drought were more likely to report reduced energy reliability and greater dependence on NRUI, highlighting the interplay between climate stress and resource vulnerability. Education levels and access to formal infrastructure emerged as significant predictors of improved WAI and EAI scores, thereby underscoring the structural determinants of household resilience.

These results directly contribute to the achievement of Sustainable Development Goals (SDGs) 6 (clean water and sanitation), 7 (affordable and clean energy), 13 (climate action), and 15 (life on land). Persistent deficits in water and energy access hinder the targets of SDGs 6 and 7, while increased reliance on natural resources in climate-stressed rural areas exerts additional pressure on ecosystems, complicating progress towards SDG 15. The identified climate-resource linkage further emphasises the urgency of aligning adaptation planning with SDG 13. Therefore, policy responses should prioritise decentralised water infrastructure, off-grid renewable energy systems, and ecosystem-based adaptation strategies tailored to rural settlements. Such interventions must be integrated within South Africa's National Development Plan and climate adaptation frameworks to ensure coherence across sectors.

Effective implementation necessitates coordinated action from key institutional actors, including local municipalities, the Department of Water and Sanitation (DWS), and the Department of Cooperative Governance and Traditional Affairs (CoGTA). Municipalities ought to incorporate WEF-based household indicators into Integrated Development Plans (IDPs) to more effectively address infrastructure backlogs. The DWS can bolster rural water security through investments in small-scale supply schemes and groundwater monitoring, whereas CoGTA can facilitate improved intergovernmental alignment and community-based planning mechanisms. By operationalising composite WEF indices at the household level, this study presents an evidence-based tool for identifying priority areas, enhancing accountability, and promoting equitable, climate-responsive resource governance.

5.1. Study limitations

Although the WAI, EAI, and NRUI provide meaningful frameworks for comparing households' access to essential resources, they are constructed on weighted variables that are unable to encapsulate every aspect of access or sustainability. These indices reflect relative differences rather than absolute measures of quality or reliability. The weighting scheme is inherently subjective, relying on expert judgement and assumptions derived from existing literature, which may influence the interpretation of results. Furthermore, the study's reliance on cross-sectional data and the utilisation of self-reported household data introduce potential biases, including recall errors, social desirability effects, and variations in the interpretation of survey items. While perceptions of environmental change were included, the study did not incorporate direct ecological data such as rainfall records or evidence of forest degradation, nor did it include direct environmental or infrastructure data. The integration of such data in future research to triangulate perceptions could provide a clearer connection between community observations and the environmental changes that are actually occurring.

6. Declarations

Author Contributions: Conceptualisation (L.M.); Literature review (L.M. & S.P.M.); methodology (L.M.); software (L.M.); validation (L.M. & S.P.M.); formal analysis (L.M.); investigation (L.M.); data curation (L.M.); drafting and preparation (L.M.); review and editing (S.P.M.); supervision (N/A); project administration (L.M.); funding acquisition (N/A). All authors have read and approved the published version of the article.

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Conflicts of Interest: The authors declare no conflict of interest.

Data Availability: The data are not publicly available due to confidentiality agreements with participants and ethical restrictions imposed by the Institutional Review Board. However, de-identified data can be made available from the corresponding author upon reasonable request, subject to approval by the ethics committee.

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